Global two-fluid simulation of tokamak Scrape-Off-Layer turbulence

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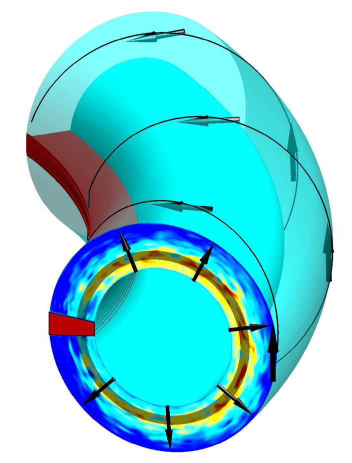
1- Introduction

- the Scrape Off Layer (SOL) turbulence is studied by means of a linear eigenvalue solver and the non-linear Global Braginskii Solver (GBS) code
- we identify the linear phase space of the SOL, finding the regions of existence of the Drift Waves (inertial and resistive) and the Ballooning (inertial, resistive and ideal) instabilities
- we focus on the effect of magnetic shear on both the linear and the non-linear dynamics
- linear calculations and non-linear simulations including electromagnetic effects are described

2- The Global Braginskii Solver (GBS) code

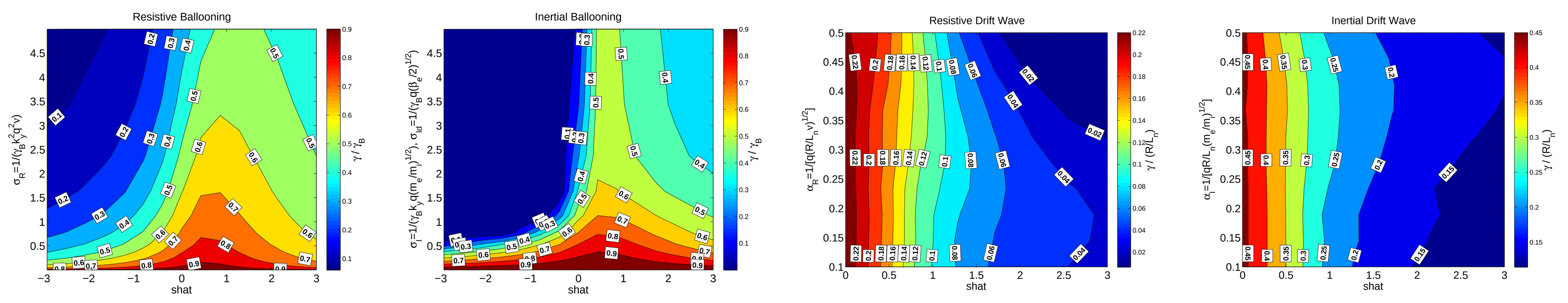
- the code is based on the non-linear, drift-reduced two-fluid Braginskii equations ([2] and [3])
- self-consistent global evolution of equilibrium and fluctuations
- we study the SOL turbulence as the self-consistent result of plasma source from the core and losses at the limiter plates

  - open magnetic field lines, ending on a limiter
  - $T_i \ll T_e$, cold ion limit
  - $\beta \neq 0$, electromagnetic effects
  - simple, circular magnetic geometry
  - $\epsilon \ll 1$, large aspect ratio approximation
  - coordinates: $x \rightarrow$ radial, $y \rightarrow$ binormal, $z \rightarrow$ parallel



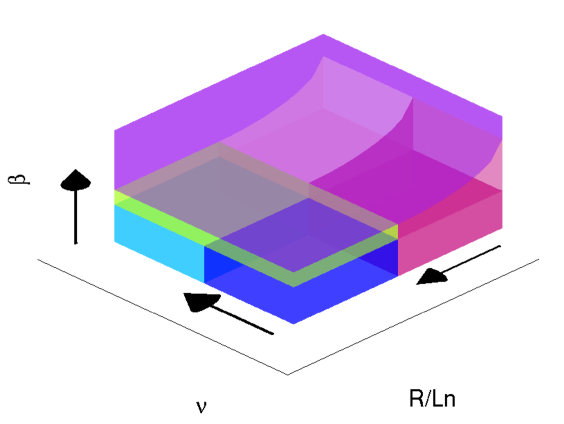
4- Linear analysis

main instabilities



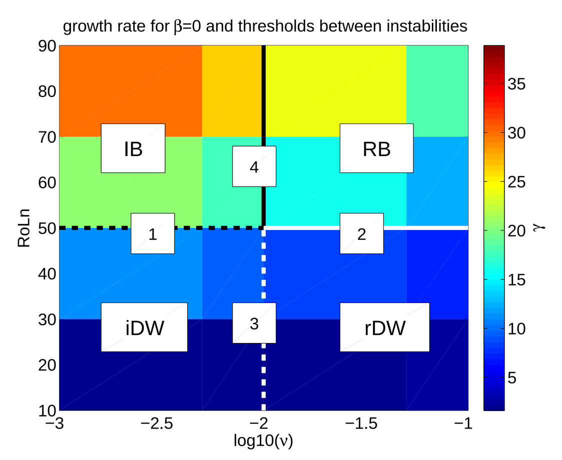
- effect of the shear on the Resistive Ballooning instability
- effect of the shear on the Inertial and Ideal Ballooning instability
- effect of the shear on the resistive Drift Wave instability
- effect of the shear on the inertial Drift Wave instability

phase space

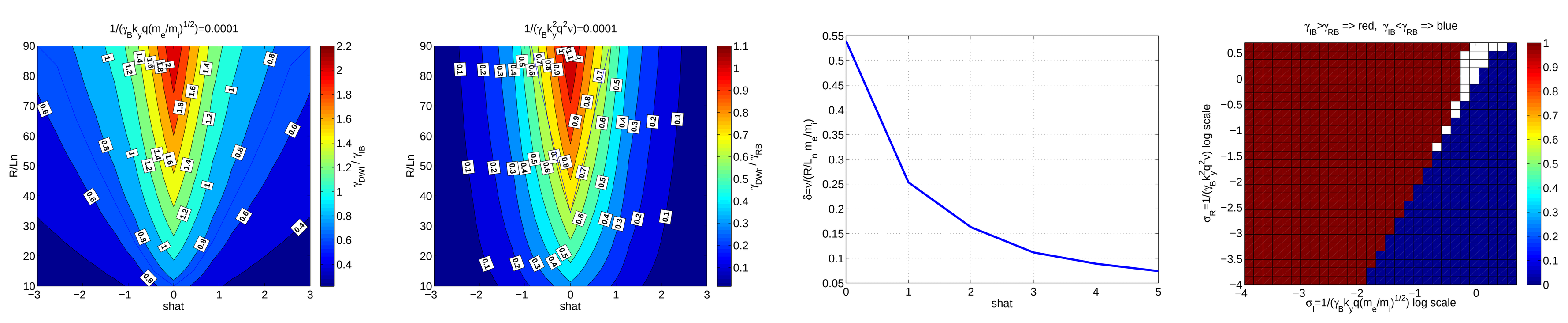


Regions of existence of the instabilities as a function of ν, R/L_n and β:

- Resistive Ballooning
- Inertial Ballooning
- Ideal Ballooning
- Resistive Drift Wave
- Inertial Drift Wave
- region of suppression of the Drift Wave



thresholds



- 1 => threshold between the inertial Drift Wave and the Inertial Ballooning
- 2 => threshold between the resistive Drift Wave and the Resistive Ballooning
- 3 => threshold between the resistive Drift Wave and the inertial Drift Wave
- 4 => threshold between the Resistive Ballooning and the Inertial Ballooning

Thresholds related to electromagnetic effects:

- suppression of the Drift Wave instability for $\frac{\beta}{2\nu}\frac{R}{L_n}(1+1.71\eta) > 1.17$ in the resistive case and for $\frac{\beta}{2m_e/m_i} > 0.17$ for the inertial case
- development of the Ideal Ballooning instability for $\alpha_{MHD} = q^2\beta\frac{R}{L_n}(1+\eta) > 1$

6- Conclusions

- identification of the linear phase space
- non-linear simulations with shear verify steepening of the gradients and suppression of the instability
- non-linear simulations including electromagnetic effects show steepening of the gradient and approach the linear condition for Drift Wave suppression

3- The drift-reduced Braginskii equations [1]

$$\text{Continuity: } \frac{\partial n}{\partial t} = \frac{c}{B}[\Phi, n] + \frac{c}{eRB}\left(\hat{C}p_e - n\hat{C}\Phi\right) - \nabla_{||}\left(nV_{||e}\right)$$

$$\text{Vorticity: } \frac{\partial \nabla_\perp^2 \Phi}{\partial t} = \frac{c}{B}\left[\Phi, \nabla_\perp^2\Phi\right] + \frac{B}{m_i cnR}\hat{C}p_e - V_{||i}\nabla_{||}\nabla_\perp^2\Phi + \frac{m_i\Omega_{ci}^2}{e^2 n}\nabla_{||}j_{||}$$

$$\text{Ohm's law: } m_e n\frac{\partial V_{||e}}{\partial t} + \frac{en}{c}\frac{\partial \psi}{\partial t} = m_e n\frac{c}{B}\left[\Phi, V_{||e}\right] - m_e nV_{||e}\nabla_{||}V_{||e} - T_e\nabla_{||}n + en\nabla_{||}\Phi - 1.71n\nabla_{||}T_e + \frac{\nu m_i}{e}j_{||}$$

$$\text{Parallel ion velocity: } \frac{\partial V_{||i}}{\partial t} = \frac{c}{B}\left[\Phi, V_{||i}\right] - V_{||i}\nabla_{||}V_{||i} - \frac{1}{nm_i}\nabla_{||}p_e$$

$$\text{Electron temperature: } \frac{\partial T_e}{\partial t} = \frac{c}{B}[\Phi, T_e] + \frac{2c}{3eRB}\left(\frac{7}{2}T_e\hat{C}T_e + \frac{T_e^2}{n}\hat{C}n - T_e\hat{C}\Phi\right) + \frac{2T_e}{3en}0.71\nabla_{||}j_{||} - \frac{2}{3}T_e\nabla_{||}V_{||e} - V_{||e}\nabla_{||}T_e$$

$$\text{Parallel gradient: } \nabla_{||} = \frac{\partial}{\partial z} + \frac{\bar{B}}{B^2}\times\nabla\psi\cdot\nabla$$

$$\text{Curvature operator: } \hat{C} = -2\left[\sin\theta\frac{\partial}{\partial x} + \left(\sin\theta\frac{y\hat{s}}{a} + \cos\theta\right)\frac{\partial}{\partial y}\right]$$

5- Non-linear simulations

electrostatic, without shear

$\hat{s} = 0$, electric potential

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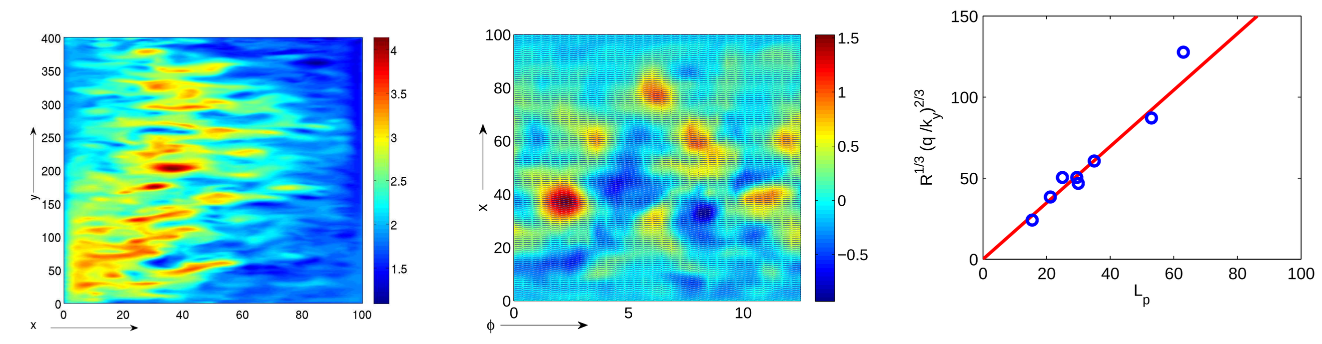
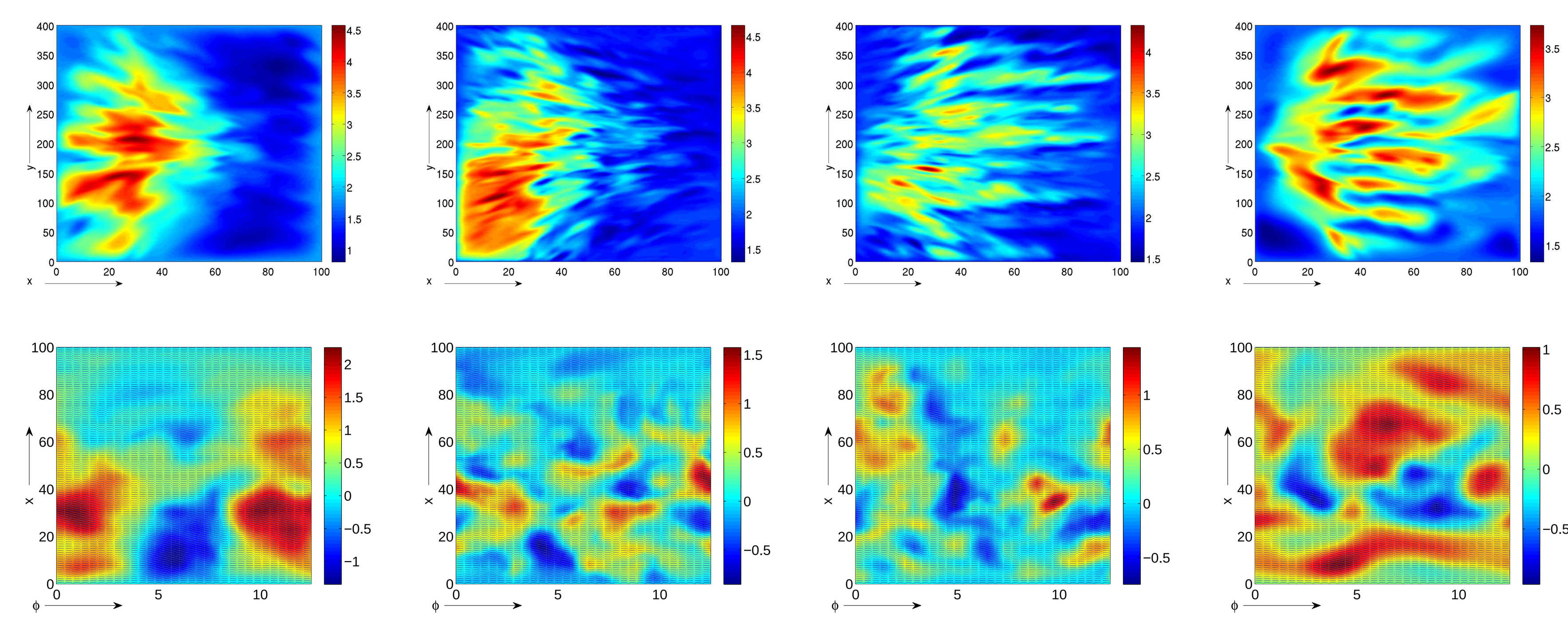


- simulation parameter: $q = 4$, $\nu = 0.1$, $m_i/m_e = 200$, $L_y/\rho_s = 400$, $R/\rho_s = 500$, $L_n = 48.50$, $L_t = 75.45$, $L_p = 29.52$
- the non-linear saturation mechanism of these simulations has been analyzed by B. Rogers and P.Ricci ([4]): $L_p \sim R^{1/3}\left(\frac{q}{k_y}\right)^{2/3}$

electrostatic, with shear

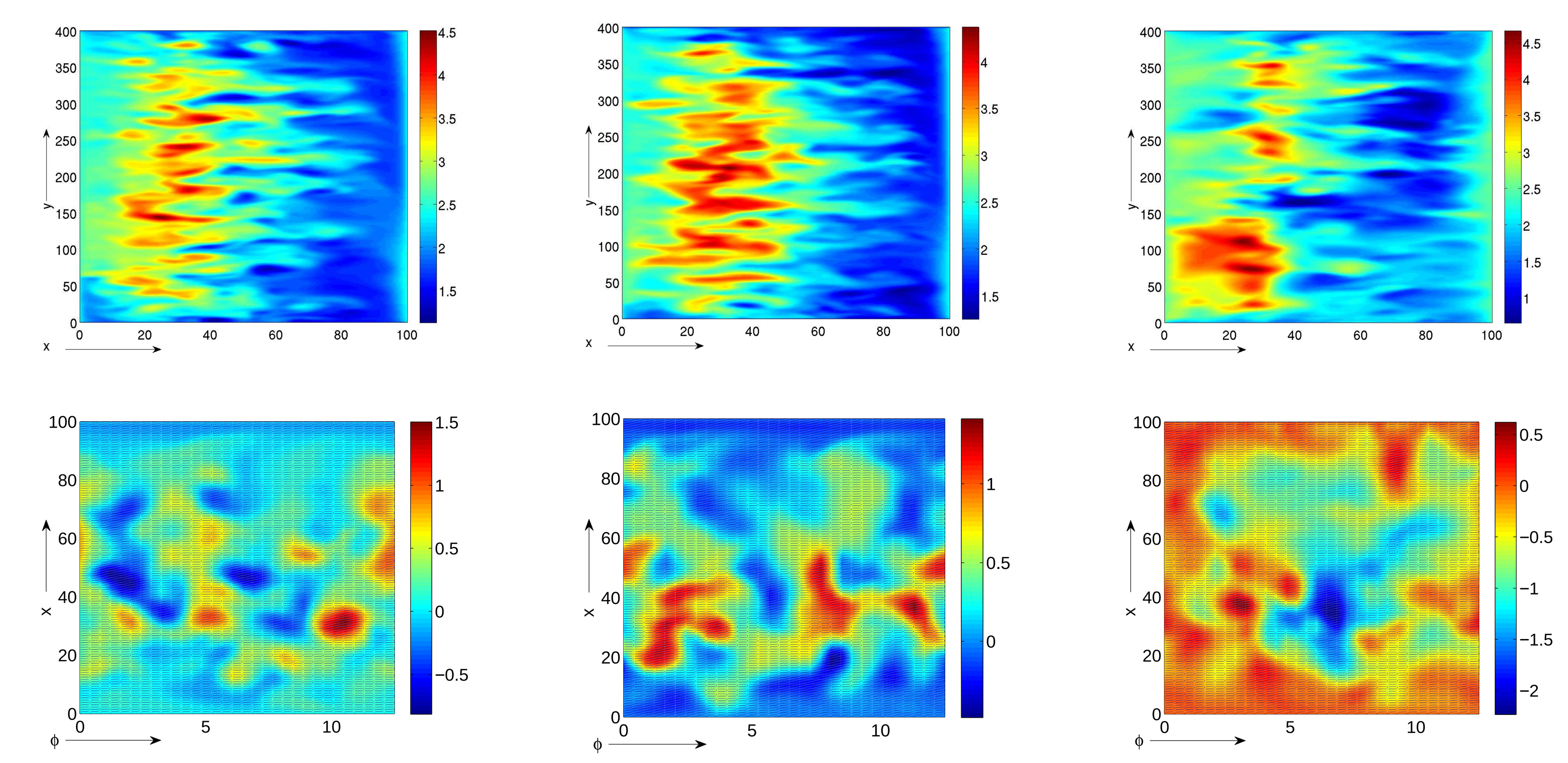
$\hat{s} = -2$ electric potential | $\hat{s} = -1$ electric potential | $\hat{s} = 1$ electric potential | $\hat{s} = 2$ electric potential



- $L_n = 32.34$, $L_t = 35.03$, $L_p = 16.81$
- $L_n = 32.34$, $L_t = 45.81$, $L_p = 18.96$
- $L_n = 35.03$, $L_t = 72.75$, $L_p = 23.65$
- $L_n = 35.03$, $L_t = 75.45$, $L_p = 23.92$
- reduction of L_p for both positive and negative values of the shear, with respect to the shearless case, with almost constant Γ_x => damping of the instability

electromagnetic

$\beta = 1\times10^{-5}$, $\alpha_{MHD} = 0.0046$ electric potential | $\beta = 4\times10^{-4}$, $\alpha_{MHD} = 0.17$ electric potential | $\beta = 2\times10^{-3}$, $\alpha_{MHD} = 0.81$ electric potential



- $L_n = 51.20$, $L_t = 64.67$, $L_p = 28.58$, $\alpha_{MHD} = 0.0046$, $\frac{\beta}{2\nu}\frac{R}{L_n}(1+1.71\eta) = 1.15\times10^{-2}$, $\frac{\beta}{2m_e/m_i} = 1\times10^{-3}$
- $L_n = 48.50$, $L_t = 61.98$, $L_p = 27.21$, $\alpha_{MHD} = 0.17$, $\frac{\beta}{2\nu}\frac{R}{L_n}(1+1.71\eta) = 4.82\times10{-}1$, $\frac{\beta}{2m_e/m_i} = 4\times10^{-2}$
- $L_n = 40.42$, $L_t = 67.37$, $L_p = 25.26$, $\alpha_{MHD} = 0.81$, $\frac{\beta}{2\nu}\frac{R}{L_n}(1+1.71\eta) = 2.51$, $\frac{\beta}{2m_e/m_i} = 2\times10^{-1}$
- reduction of L_p with increasing β and approach of the conditions for the stabilisation of the Drift Wave

References :

[1] A. Zeiler *et al.*, *Phys. Plasmas*, Vol. 4, Issue 6, 1997

[2] B. N. Rogers and P. Ricci, *Physical Review Letters*, 104, 225002 (2010)

[3] P. Ricci and B. N. Rogers, *Physical Review Letters*, 104, 145001 (2010)

[4] B. N. Rogers and P. Ricci, Turbulent saturation and transport in global 3D two-fluid simulations of the tokamak edge, talk given at the Sherwood Fusion Theory Conference on April, 1st

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Sherwood Fusion Theory Conference, Atlanta, GA, USA, March 31-April 3 2012